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Plastic Properties Of High Performance Self-Compacting Concrete

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PLASTIC PROPERTIES OF HIGH PERFORMANCE SELF-COMPACTING CONCRETE

by

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This thesis, submitted by Kyle Seidler in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Kyle Seidler

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ABSTRACT

As the world becomes more complex and people become more evolved the desire to build taller building and design more complex structures is on the rise. The major problem that occurs with larger structures are the forces associated with building bigger. One way to help solve the problem of large stresses in concrete structures is to include more reinforcing steel and design more complex reinforcing configurations. The down side to increasing the amount of reinforcing steel is that the steel creates smaller gaps for the concrete to flow through. This problem was realized in the early 1980's and the concept of producing concrete that flows like water was brought to life, this product was called self-compacting concrete. This research will look at the plastic properties associated with the fresh properties of self-compacting concrete to ensure that the mixes have the correct flowability while maintaining its structural integrity. Also, the amount of entrained air could ultimately decide how well the structure functions in different environments. If all tests are successful and the mix is approved the material should flow through the formwork without assistance and have a proper air structure along with evenly distributed aggregate. This research shows that a material can be very fluid, but still exhibit the strength of normal concrete.

Chapter I

INTRODUCTION

Background

Concrete as a material has played a significant role in constructing buildings, simplifying means of transportation, and advancing infrastructure to propel society into a modern age. For years, uniform procedures have compounded aggregates, water, and Portland cement to produce a product that can withstand thousands of pounds of pressure, without compromising its structural integrity. While this combination of materials may be popular in the structural engineering industry, a problem that occurs is the composition of the mixture doesn't allow it to flow through tight sections of formwork. To counteract this problem, the mixture of aggregate and cement can be altered to flow like water through the formwork, and seal the voids that may be left, due to sharp angles or large rock. This type of water-like mixture is known as self-consolidating concrete (SCC) or more commonly known as self-compacting concrete. Furthermore, normal concrete requires more manpower to ensure the product performs correctly, and withstands pressure. In contrast, the self-compacting concrete will help reduce man power and physical labor. As a result, this product will improve the cost-effectiveness of concrete application, and decrease chances of human error.

Problem Statement

While this product is currently utilized in today's civil engineering industry, there is little research that supports how well it works. The objective of self-compacting concrete is to flow under its own weight, since these materials need to meet very strict guidelines to achieve the hardened properties of concrete. Since self-compacting concrete is relatively new to the construction world, there has been very little research conducted to determine the desired plastic properties of high performance self-compacting concrete.

Objectives

This research will focus on the properties of the SCC mixture before it begins to solidify inside the formwork. An implication of this study is to elevate the benchmark of this product's quality. The tests that will be performed are as follows: a spread test, J-ring test, air content test, and compressive strength test. First, the spread test proves that the mix flows like water, and does not stick together in the shape of a cone like normal concrete. Second, the J ring test will test how much the aggregate separates when the mixture flows between the different sections of the ring. The problem with creating mix that flows well is that the larger particles in the mix tend to separate out, thus producing a mix with limited strength. Once a fluid mix is developed, the air content of the mix needs must be tested to ensure the proper ratio of voids exist. Finally, the strength of mix will be tested to ensure the materials achieve the desired strength of 6000 psi.

Thesis Organization

Chapter I gives a slight background of self-compacting concrete and the overall objective of the research. Chapter II expands on Chapter I and gives a more detailed background on the material along with providing an explanation of each test method that could be used to test the self-compacting concrete mixes. Chapter III deals with methodology which includes material selection, mix design and data analysis. Chapter IV is the actual results and comparison between mixes. Chapter V includes the conclusion, limitations and future work.

Chapter II

Literature Review

Self-Compacting concrete was first used in Europe in the 1970's; however, data shows that most research and understanding of Self-Compacting Concrete was not completed until the 1980's when Japan began using Self-Compacting Concrete to reduce the labor forces needed to complete large concrete projects (Naik, 2011). In 1986 a professor by the name of Hajime Okamura proposed an idea that a concrete could be designed that would flow like molasses. However, it would take another two years for a prototype to be developed by professor Ozawa at the University of Tokyo in Japan (Dehn et al., 2000).

The down side to designing and building with concrete was that for concrete to be effective in tension rebar needed to be placed strategically throughout the forms to pick up any tensile stresses. When the steel reinforcement is placed in the formwork it creates a maze that the concrete must flow through to ensure all voids are filled. Normal weight concrete and Self-Compacting concrete have very similar hardened properties; however, to get the normal weight concrete to flow through the formwork and fill all voids workers must vibrate the concrete to encourage the mixture to become more fluid. Self-Compacting Concrete on the other hand is very fluid and will compact and flow under its own weight and does not require the use of additional vibratory methods either internal or external even in the presence of congested reinforcement (Ramanathan, 2013).

Self-Compacting Concretes, in principle, had been used many years prior to 1980; however, they were only used in special applications like underwater pours where vibrating the concrete would have been completely impossible (Bartos, 2000). To achieve a mixture that would perform under certain conditions a large amount of cement paste would be added to a standard mix design and placed into position with the use of a tremie chute to ensure that the concrete would not segregate. Segregation was a major concern for early designs since the only way known to make concrete more flowable was to essentially increase the w/c ratio which would allow the material to flow better; however, this allowed the cementitious material to separate from the rock. This led to the development of modern day self-compacting concrete. The desire to make a product that could be placed in any environment and flow easily through formwork under its own weight became a desirable product for contractors and engineers. The proposal provided by Hajime Okamura in 1986 gave multiple agencies and companies the ability to begin designing and testing self-compacting concretes in their own labs in the hope of developing a mix design that would meet standards set by the ACI code (Dehn et al., 2000).

Concrete placement was starting to become a major problem since structures were getting larger and the amount of reinforcement required was becoming more complex. Since the amount of reinforcing steel required to complete the more complex designs was limiting the available flowable space for concrete, more man power was required to get the concrete mixture to flow into all the spaces. In fact, two researchers at the University of Tokyo, Ozawa and Mackawa, discovered that the main reason concrete failed was due to poor placement and compaction of the product, not the design (Bartos, 2000). They determined that for concrete to continue to be the durable product, we have come to know and understand, we must design a concrete mix that will flow better and pack into every corner of the formwork under its own weight. Another option to consider is using only

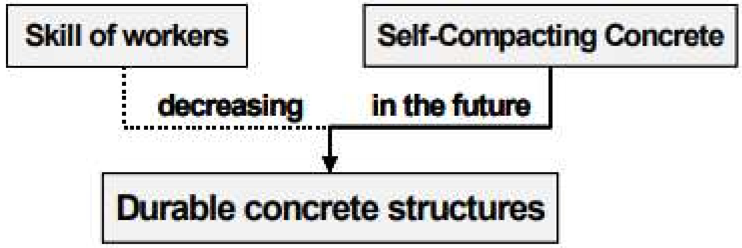


Figure 1 Concrete Workflow (Ouchi, 1996)

the highest skilled workers to place the concrete at every building site. Since the world was expanding and structures were only going to get bigger and more intricate, and the number of skilled workers was not going to grow, but would decrease, as figure 1 shows, it was determined a material should be designed that most employees would be able to place without any error.

Testing Methods

Once a design was established there needed to be a certain set of regulations and standards that needed to be met by each design to ensure that the correct percentage of aggregates, cementations materials, and water were used. To make the process simple Ozawa and Mackawa established six simple tests that can be performed in the lab when designing a mix or in the field when an engineer needs to check the fresh mix out of a truck. These six tests are designed to focus on three major factors of self-compacting concrete; resistance to segregation, passing ability, and filling ability. The ability to fill voids and the ability to pass through small sections are easy to alter by adjusting the size of aggregate that was used. However, resistance to segregate was harder to achieve since that cannot be altered just by adjusting the size of rock and the amount of water in the mixture. These tests ensured that a proper mix would be designed and all proper standards were met. The tests the tests that were designed are Slump Flow, U-Type, L-Box, V-Funnel Test, and Slump Flow/J-Ring Combination Test.

U-Type Test

The U-Type test consists of a box that is built and shaped like a U, as seen in Figure 2. The box is filled on the left side while the gate is closed to ensure the material stays on one side. The material is to be added in one even lift and no vibrating or tamping is to be performed on the specimen. Then, the gate is lifted to allow the self-compacting concrete to flow between the rebar placed at the bottom until equilibrium is reached. For this test to be considered successful the concrete must flow to the other side of the box and reach a height greater than 300 mm (Standard Test, n.d.)

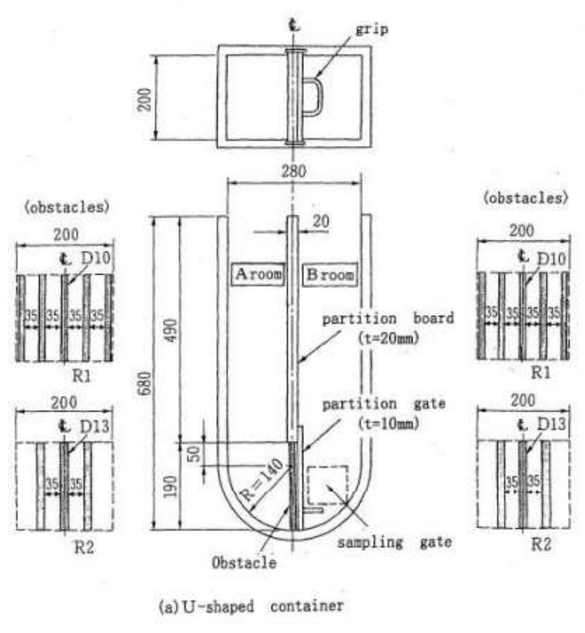


Figure 2 U Type Test Apparatus (Standard Test, n.d.)

L-Box Test

Like the U-Type test the L-Box is a test that is used to determine the filling ability along with passing ability as seen in Figure 3. However, unlike the previous test this test will determine how well the concrete flows in the horizontal direction. The goal is to have a mixture that will flow away from the gate without any evidence of segregation in the rock. While this test is performed the time is recorded for the mix to flow 200 mm in the horizontal direction and the time for the mixture to reach 400 mm. While the objective is to have the concrete reach the 200mm and 400mm range it is also important that the mix does not segregate and that when the mix ceases to flow that the mixture lay flat in the testing apparatus (Standard test, n.d.).

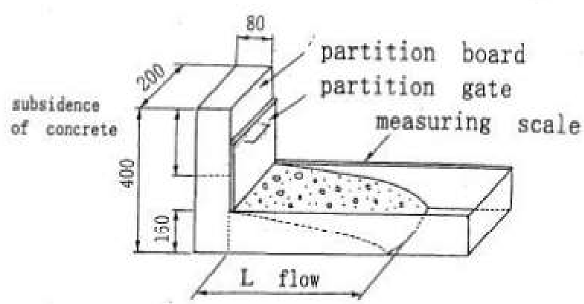


Figure 3 L-Box Apparatus (Standard test, n.d)

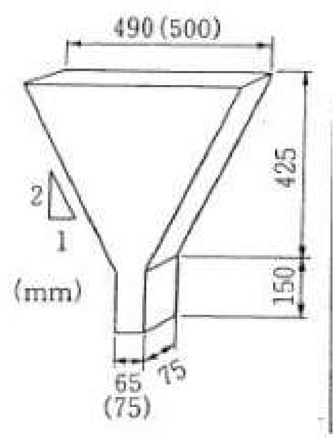


Figure 4 V-Funnel Test (Standard test, n.d)

V-Funnel Test

This test will give the average-flow through speed of the self-compacting concrete. This test consists of an apparatus that can be seen in Figure 4. The funnel shall be wet to allow the concrete to flow across the surface without any surface friction. Once the apparatus is washed the funnel shall be placed completely vertical. The concrete mix is then poured into the funnel until mix is level with the top edge. Once full the bottom flap is opened within 10 seconds of filling and the time until all the concrete has flown through the opening is recorded. This test along with the U-Flow and L-box were derived in Japan and determined to be an adequate test for fresh self-compacting concrete and all information was provided by an article published by Japan Society of Engineers (Standard test, n.d).

The Slump Flow Test

ASTM C1611/C1611M; The slump flow test is used to measure the spread of the self-compacting concrete along with determining if bleeding has occurred or whether the rock has resisted segregation. This test consists of using a mold, same mold used in the slump test of normal concrete, and a flat surface. For a successful test the cone must be placed on a flat level surface. The ground beneath the cone should be wet to allow the mixture to flow freely across the floor. Next the mix should be placed in the cone in one lift, without vibrating or tamping the mixture. Once filled, the mold is lifted off the ground allowing the mixture to spread across the floor. After the mixture has stopped spreading one measurement is taken in each direction and the average of the two is recorded. The target is to have a spread that is as close to 24 inches as possible. Once the mix has ceased to spread and measurements have been taken a visual exam of the spread must be done. If the mix has hit the target spread, 24 inches, without showing signs of bleeding then more tests can be performed. However, if bleeding is present, water sitting on the surface, then the mix must be altered to reduce the amount of water or adjust the mix so more water is absorbed, see Figures 15 and 16 in the appendix. Figure 15 shows a proper spread along with no bleeding. Figure 16 shows that the rock did flow, however water is still running off of the mix at the edge of the spread. Secondly, the aggregate must be spread evenly through the mix and not piled in the middle where the cone was placed. If aggregate sits in a pile under the cone the mix needs to be altered to ensure the aggregate and cementitious material do not segregate as seen in Figures 17 and 18 in the appendix. Figure 17 shows a test mix that segregated, the pile of rocks in the middle did not flow with the mix to the edge of the spread. Where as in Figure 18 the aggregate stuck with the cementitious material and got dispersed evenly though out the spread.

Slump Flow with J-ring

ASTM C1621/C1621M – is a test that has been adopted by the American Society for Testing Materials. This test involves using the cone from the slump flow test along with a specially designed ring that can be seen in Figure 5 and Figure 19. Figure 19 gives

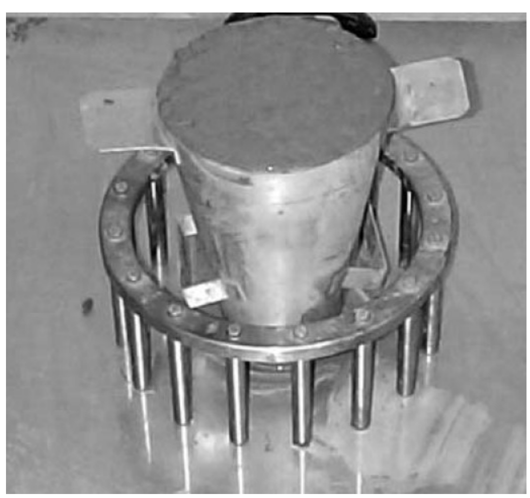


Figure 5 Slump Flow with J-Ring Apparatus (ASTM C1621))

the spacing of the bars which represents the voids the self-consolidating concrete must flow through. Just like the slump flow test the concrete is to be placed in the inverted cone apparatus in one lift without being vibrated or tamped. Once filled, the cone is lifted from the ground allowing the self-compacting concrete to flow in each direction toward the j-ring. The concrete should flow through the j-ring and continue to flow under its own weight until coming to rest. The time it takes for the concrete to stop flowing, along with the average of the spread in the longest and shortest direction should be recorded. The spread-out concrete should also have the same consistency throughout the entire mix and all aggregate should pass freely between the vertical bars on the j-ring, for the mix to be considered successful all the prior criteria must be met (ASTM C1621). The prior two tests are adopted by the ASTM and therefore can be used on any jobsite to test self-compacting concrete for flowability, segregation, and filling ability.

Air Meter

ASTM C231- Since it is impossible to visually test the amount of entrained air in a concrete mix, an apparatus has been developed that will give an accurate approximation

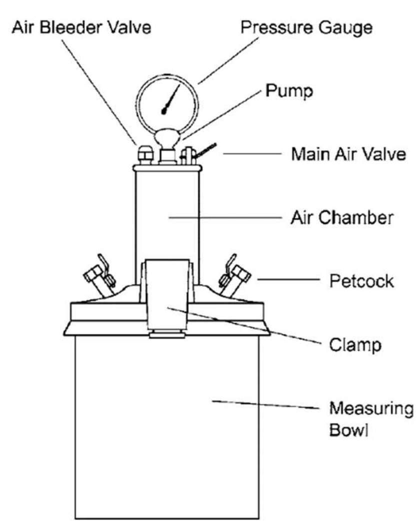


Figure 6 Pressure meter (ASTM C231)

of entrained air. There are a couple of different testing apparatuses available on the current market that give the same result, however the most commonly used test is the pressure meter test whose apparatus can be seen in Figure 6. The pressure meter uses the theory that the only component of the mix that is compactable is air. Once the pot is pressurized, to twice that of atmospheric pressure, the only component that can change in the sample is volume of entrained air. For the test to be successful a careful procedure must be followed and any slight deviation can cause inaccuracies. The first step to ensuring a successful test is for the apparatus to be cleaned completely. Once the pot and lid are clean the pot should be wetted down with a sponge. After that, the apparatus is ready for the concrete mix to be placed into the pot until the mix sits just above the rim, again the self-compacting concrete should be placed in one lift. After the pot is full take a flat piece of plexi-glass and moisten one side. Take that same piece of plexi-glass and strike off the top of the mix to ensure the mix fills the pot completely but does not overflow. A wet sponge should be used to clean the edge of the pot so proper contact can be made with the lid to ensure the lid has an air tight seal. Place the lid atop the pot and lock down two clamps opposite each other at the same time, this helps the lid fit squarely on the pot and minimizes the chances of failure. Once all four clamps are locked, open both petcocks and slowly add water in one side. Once the water flows out the opposite petcock stop filling and allow the water to stop flowing from both petcocks, after the water ceases to flow close both petcocks. Now secure the nut on the top of the apparatus to ensure that the apparatus is air tight. Begin to pump the apparatus full of air until the gauge reads .2 psi more than the desired test pressure. Once the desired pressure is reached allow the sample to sit for a couple seconds to ensure the gauge holds that pressure. If the gauge holds strike the relief valve on the top of the column and document the percentage of entrained air. If done correctly and precisely, data has shown that result can be within 5-10% from the same concrete sample (Hover, 1993).

Mineral Admixtures

In the last 20 years, the mix design of concrete has evolved from consisting of only aggregate, cement, and water to a mixture consisting of the three traditional materials along with the addition of byproducts that would just be considered hazardous waste. It was determined that fly ash, blast furnace slag, and silica fume could be added into self-compacting concrete in replacement of the traditional cementitious material. It was also determined that these byproducts would be disposed of in a safe and timely manner along with increasing the strength and flowability of the concrete (Sua-iam, 2015).

Fly Ash

The first mineral admixture that will be looked at is fly ash. Fly ash is a byproduct of the combustion of coal along with various gases (User Guidelines for Waste, 2008). Power plants produced 120.6 Million Tons of fly ash in the year 2015 with the federal highway administration consuming 23.5 Million Tons of fly ash. That number is projected to increase to 35.6 Million Tons of fly ash by 2033 (Black, 2015). This residue, fly ash, is considered a hazardous material that must be handled with caution and disposed of in ways that cost energy companies thousands of dollars which in turn drives the price of energy up for the consumers. Along with saving tax payer's dollars, the use of fly ash has many positive effects on the self-compacting concrete. It has been seen that the use of fly ash in self-compacting concrete has reduced the number of chemical admixtures needed to obtain the desired flow rate (Khatib, 2007).

Blast Furnace Slag

Blast furnace slag is a nonmetallic coproduct produced in the process of smelting steel. It consists mostly of silicates, aluminosilicates and calcium-alumina-silicates. The main use of blast furnace slag is to produce Portland cement and the percentage of replacement and guideline for use is controlled by AASHTO M302 (User Guidelines for Waste, 2008). With the use of blast furnace slag in self-compacting concrete mixes, the amount of waste the steel mills produced has dropped drastically. On average the steel industry produces around 250 million tons of slag per year, the concrete industry is responsible for the consumption of 90 million tons a year or around 36% (Boukendakdjii, 2011). As the use of self-compacting concrete increases with the world's desire to build bigger, the number of dangerous products that leave the steel mill around the world will increase, however the amount of blast furnace slag safely incased in concrete will also increase (Boukendakjii, 2011).

Silica Fume

Silica fume is a byproduct of the smelting process in the silicon and ferrosilicon industry (Khan, 2011). Silica fume is a product that is finer than many of the particles that are used in the creation of standard Portland cements. This allows for the particles to flow through the concrete mix and have more surface contact with the aggregates and other products that are placed in self-compacting concrete mixes. Since the particles are very fine, as they are mixed in within the concrete they help fill voids that are left by the larger aggregates of the self-compacting concrete mixes. With there being less uncontrolled air-voids, this allows the products to become more predictable and gives a higher chance of a desired and successful outcome. While the size of silica fume makes the material very desirable, the chemical and reactive properties also make the use of silica fume practical. When the silica reacts with the lime that exists in the Portland cement calcium silicate hydrates are formed. When these hydrates are joined they create a very strong and durable matrix, which when cured help increase the overall durability of the self-compacting concrete mix. However, while these chains are very strong at rest, once a force is applied to the matrices they break down and become very fluid until they are back in a resting state where they become strong once again (Benaicha, 2015). The ability to go from a fluid state to a very strong solid state make silica fume a great candidate for the self-compacting concrete mix. There are also chemical admixtures that can be added to the mix while in its plastic state to help ensure successful results.

Chemical Admixtures

Chemical admixtures are liquids that can be added into a concrete mix while in the mixer to help control and make the plastic properties more predictable. They have many different roles, like the mineral admixtures, and each one requires an understanding of the material to ensure proper dosage (Ramanathan, 2013). Unlike the mineral admixtures the cost of the chemical admixtures is very high therefor the proper dosage is very important. Also, since these are in liquid form the can influence the water cement ratio and cause problems with the mix instead of helping achieve desired results (Felekoglu, 2007).

Superplasticizers

Superplasticizers are chemical admixtures that are used to help reduce the amount of water needed to create a more fluid mixture. Since these chemicals help reduce the amount of water needed for a successful mix they are often referred to as “High Range Water Reducers”. When the idea of self-compacting concrete was presented, the initial thought was to take an existing concrete mix and reduce the aggregate size. However, Okamura proposed the idea that a mortar should be produced that flows consistently. Once the mortar was altered and the results were tested it was determined the same concepts could be taken and applied to normal concrete mixes (Dubey, 2013). After many tests it was determined that the superplasticizers allowed the mix to become more fluid without altering the water content of existing mix designs. The self-compacting concrete mix became so fluid that the aggregates were observed to segregate slightly (Shen, 2014), thus the idea of viscosity modifying admixtures was introduced to help prevent segregation.

Viscosity Modifiers

Viscosity modifying admixtures can and should be used alongside superplasticizers to help enhance the self-compacting concrete. This type of admixture is placed in the mix to help reduce the chances of segregation while increasing the flowability of the mix. The viscosity modifier helps prevent the segregation due to the changes that they cause within the internal chemical reactions. The viscosity modifying admixtures help the polymer chains become more entangled which in turn lowers the internal shear-thinning behaviors. When the internal shear decreases the liquid state of the mixture becomes more plastic and the components of the mix tend to stick together preventing the mixture from segregating (Lachemi, 2003).

Air Entrainment

Since the mix design of self-compacting concrete generally consists of using fine particles along with smaller rock the compaction that gets developed is very good. However, since the particles fit together tighter this leaves a very low content of air that is trapped within the mix. Through many years of study and practice it has been noticed that as the amount of air entrapped in the concrete decreases the compressive strength increases. Research has shown that as the concrete gets exposed to external elements like freezing and thawing the lower the air entrainment, the worse the concrete performs (Ziari, 2017). Throughout many years of research, it has been determined that the proper air entrainment percentage should fall between 4.5% and 6% depending on the climate where the concrete will be placed (Puthipad, 2017).

Since self-compacting concrete has fine particles that fit together tightly an admixture can be used to help ensure the mix contains enough entrained air. Early air entrainment admixtures used a concept of creating foam to help take up space between the molecules ensuring that when the mix settled a proper percentage of voids were present. However, the size of voids and distribution of these voids was very hard to control and develop consistent mixes, more recent research states that if the foam can be reduced the bubbles that are left can be controlled and a more stable mix can be developed (Puthipad, 2017).

While making the mix more stable the smaller particles also help the plastic properties of the self-compacting concrete mix. The little air bubbles that are left tend to be completely round and have very few defects also, they are more dispersed and evenly spread out creating a bearing effect on the mix. As the particles flow the little balls allow the surface friction to be reduced which makes for a higher spread. Since the friction is reduced this also helps reduce the amount of segregation that is developed between the larger particles of the mix (Puthipad, 2017). While the ability to control the bubbles gives a greater control of the mix it also does require a higher amount of air-entrainment admixture to account for the shrinkage that accompanies the defoaming agent (Ziari, 2017).

Chapter III

RESEARCH METHODOLOGY

Materials

The most important part to any concrete mix, whether it be self-compacting or normal strength concrete, are the materials that go into the mix. There are many different aspects that could end up causing failure of a concrete mix and generally the ultimate reason for failure is due to not understanding or analyzing the materials that get used in the mixes. To keep the costs and quality of the materials consistent, all the materials that were used to conduct the following mixes were obtained from either North Dakota or Minnesota. As seen in Figure 7 the aggregate was rather dirty and needed to be sieved to ensure that the appropriate size was used. Also since there were so many fine particles in the aggregate, it was washed and allowed to dry before being used in the mix.

Figure 7 Aggregate from Strata

Coarse Aggregates

Coarse aggregates are any material that does not pass the 3/8” sieve. The coarse aggregate that was used for the self-compacting mix study was obtained from the Aggregate Division of Strata Corporation in Grand Forks, ND. This aggregate was retrieved from a pit just outside of Grand Forks and crushed on site to a smaller and more manageable size. This aggregate was tested by Midwest Testing Laboratory in Grand Forks and it was determined that the aggregate met the specific gradation for ASTM C33, size 57 and size 67 coarse aggregate. The gradation also met the standards for the North Dakota Department of Transportation 816.02, size 3 and size 4 coarse aggregates. The specific gravity of the aggregate was 2.67.

Fine Aggregates

A fine aggregate is classified as any material that passes the 3/8” sieve and almost entirely passing the #4 sieve, but not passing the #200 sieve. In most cases of concrete design, a certain percentage of fine aggregate would be mixed with a certain percentage of the coarse aggregate to produce a defined ratio and this mixture would be considered the aggregate. However, for the sake of this research the fine and coarse aggregate were not separated. The fine aggregate was also obtained from the Aggregate Division of Strata Corporation in Grand Forks, ND. The sample was also tested by Midwest Testing Laboratories and determined that the aggregate met the gradation specification for ASTM C33 fine aggregates along with NDDOT 816.01 fine aggregates. Since the fine aggregates came from the same pit as the coarse aggregate they were also tested by Midwest Testing and had a specific gravity of 2.67.

Cement

Cement is a powdery substance that is made with calcinated lime and clay. The cement gets mixed with water to create a hydrate, that hydrate reacts with the surface of the aggregate to form the bonds that hold the mixture together. Throughout the design process a Type I TCC Portland cement was used. Type I cements are the most common type of cements used throughout the Dakotas and Minnesota that is why it was chosen for this design. The cement used met all the requirements as outlined by ASTM C150 for cement binders. The specific gravity of the cement used was 3.15.

Superplasticizer

The superplasticizers were one of the main sources that were adjusted throughout the project. Since every mix behaves slightly differently the superplasticizer is a simple way to make minor alterations after all the aggregates and water have been combined. During this study two different types of superplasticizers, also called high range water reducers, were used. The first superplasticizer that was used is known as a Type A superplasticizer. This superplasticizer is responsible for reducing the amount of water needed to produce a successful mix. While doing the literature review for the mix designs it was seen that most Type A superplasticizers can reduce the amount of water needed for a mix anywhere from 5% - 12% (Goguen, 2013). The product chosen was Pozzolith 322N ready-touse. This product meets all the current requirements set forth by ASTM C494 and C494M.

The second superplasticizer used was categorized as Type F. Similar to the Type A superplasticizer, Type F also reduces the amount of water needed to complete a successful mix. This superplasticizer is known as a high-range water reducer. It is called high-range due to the fact it can reduce the amount of water needed by 12% all the way up to 30% in some cases (Goguen, 2013). Along with reducing the amount of water needed to complete a successful mix it also helps retard the concrete mix. Since the purpose of the self-compacting concrete is to flow consistently through the formwork we want to keep the mix fluid for as long as possible. The retarding agent in the superplasticizer allows the mix to stay fluid longer without reducing the overall performance of the finished product. The Type F superplasticizer that was used for the tests performed was a product produced by MasterGlenium called 3030 ready to-use-full-range water reducer. This product also met the standards set by ASTM C 494 and 494M.

Air Entrainment

Since self-compacting concretes are very fluid and use smaller particles, therefore the ability to keep the air structure consistent is very difficult without the use of an air entrainment admixture. For the research conducted we used a product called MasterAir AE 90. Again, while conducting the literature review for this research it was seen that the approximate amount of air entrainment admixture ranges between 4% - 7% by weight (Goguen, 2013). However, this was only a recommendation and the research performed helped determine whether that assumption was accurate.

Fly Ash

As discussed previously fly ash is a by-product of burning coal and is considered a hazardous material. Since this research is taking place in North Dakota the use of fly ash was high on the priority list for two reasons. The first reason being North Dakota is the largest producer of fly ash in the country thanks to the nine active power plants in the state therefore that makes the availability of it cheap and easy to obtain. The second reason is that the fly ash helps produce a higher quality product. The fly ash that was used in the mix designs was provided by Coal Creek Station, which is a plant located near Underwood North Dakota and operated by Great River Energy. The fly ash that is produced by Coal Creek is considered a Class C. This means the ash mainly consists of alumina and silica. This fly ash met the standard requirements set by ASTM C 618 along with having a specific gravity of 2.65.

Silica Fume

The last of the materials that were used for the tests was silica fume. It was chosen to look at the effects of the silica fume on the concrete mix in low dosages. From the literature review it was established that using more than 15% replacement would cause the mix to become tacky and prevent the mixture from flowing freely. The product chosen was MasterLife Rheomac SF 100 dry compacted silica fume, thus the goal was to keep the dosage under 5% replacement. This product met the requirements set forth by ASTM C1240. The specific gravity of the silica fume was 2.20.

Mix Procedure

Since self-compacting concrete is relatively new in the world of concrete there has not been a set of standard guidelines to follow for adding the components into the mixer. Therefore, the following process was recommended by Henry Hauge who is the Director of Technical Services with Strata in Fargo, ND.

The first objective was to prepare the aggregate for the mix. Since the aggregate was taken from a bulk holding area there were many different sizes all mixed together. Self-compacting concrete relies on the ability for the mix to flow freely through small gaps so it was determined that the max aggregate size would be ½”. To assure the max aggregate size would be ½” the rocks were run through a Gilson testing ½” screen. Once the aggregate was sorted it was placed in a wheel barrel and washed with water. This process allowed all the unwanted dust to be removed from the aggregate. This washing was repeated until the water that was used to wash the rock produced a clear runoff. Once the rock was washed, it was dumped onto a tarp on the floor and allowed to dry. Since the goal of the design was to keep the water to cement ratio as low as possible, washing the rock helped limit the amount of water absorbed by the dry aggregate.

After the rock was allowed to dry, to a point where it was considered surface saturated, the process of weighing the materials began. Each material was measured into many different 5-gallon pales to allow for easier handling of the various materials. To ensure the most accuracy in the results each bucket was rinsed and allowed to air dry. Once the buckets were dry each material was carefully placed into the bucket while the bucket sat on the scale. After the correct weight was reached the specimen was left to sit on the scale to ensure the most accurate results. Once all the aggregate and water was weighed out on the scale the admixtures were measured out using graduated cylinders. The components were taken directly to an area beside the mixer and were left there until they were needed in the mixer. This process helped ensure the least amount of cross contamination would occur between the different mixtures.

Once everything was placed over in the mixer staging area the combination of materials began. In the mixing procedure provided by Henry Hauge he stated that the air entrainment admixture should be added directly to the measured-out quantity of sand. The theory behind adding the air entrainment admixture to the sand helps ensure the dosage gets evenly dispersed through the mixture. There were a couple of different options for adding the air entrainment to the mix; however, from the literature review the most accurate and repetitive results were achieved when the air entrainment was added to the sand prior to mixing.

The next step was to take 2-3 lbs of water out and place it in a bucket off to the side to use for rinsing and adjustments, this was known as hold out water. Then the Type A high range water reducer was added into the mixing water. The holdout water would eventually be used to clean out the five-gallon buckets and graduated cylinder to ensure that all materials that got weighed out ended up in the mix.

Lastly, before we could start combining the components in the mixer the silica fume was placed on top of the cementitious material. The silica fume needed to be placed with another component of the mix due to its extremely fine composition. The silica fume would not work its way into the mix if it were added by itself due its light weight. Also, the static charge of the silica fume made the material want to stick to the metal mixer, both the weight and static charge would cause the fume to avoid being mixed into the other components and render itself useless. Placing the silica fume with the cementitious

Figure 8 Three Cubic Yard Mixer

material allowed the silica fume to adhere to the cement and use the weight of the cement to get embedded into the mix.

With all the material ready to be mixed together the only task left was to prepare the mixer to receive the measured-out components. An electric three cubic yard mixer, as seen in Figure 8, was used for all the mixing procedures. The electric mixer allowed for the material to be mixed at a constant pace and the revolutions per minute were consistent for every mix. Before any materials were added to the mixer, it was filled partially with tap water and allowed to rotate for two minutes. At that point the water was dumped and the mixer continued to spin while all the materials were added.

The first material to be added into the mixer was the coarse aggregate. After the coarse aggregate was in the mixer half of the sand with the air entrainment admixture was placed into the mixer along with the water containing the Type A superplasticizer. Once all these components were in the mixer they were allowed to mix until all the materials in the mixer appeared fully saturated. When all the aggregate was wet, the cementitious material, with the silica fume, was poured into the mixer and again the mixture was allowed to spin freely until all the materials were fully saturated. Next the rest of the sand was placed into the mix, with the first stage of combining complete, some of the holdout water was then used to rinse the buckets that contained the aggregates, sand, and the cementitious material.

Once all the materials were combined in the mixer and saturated the last product to add was the Type-F superplasticizer. The difficult part of this step was that every mix behaved slightly different therefore the exact amount needed was adjusted through visual inspection. Since the Type-F superplasticizers main use was to help increase the flowability, adding slightly less than the original quantity called for would not hurt the mix. However, if too much Type-F superplasticizer is used the product will become fluid and not stick together causing failure of the mix. To combat this, the initial amount of Type-F superplasticizer added into the mixer was never the full amount that the mix called for.

After the materials were in the mixer and the initial amount of the Type-F superplasticizer was added the mixer was allowed to spin for three minutes without any interruptions or addition of any new materials. After the initial three minutes was up the mix was examined to ensure the proper characteristics were exhibited by the self-compacting concrete at this stage. Once, the initial observations were made the mixer was then covered by a damp towel to ensure nothing else was added to the mix, this towel also served as a temperature control. Since concrete produces heat when mixed the damp towel help extract the heat from the mix and keep the mixing temperature of the concrete down. Keeping mixing temperature down helps ensure the maximum performance of the hardened properties.

After the 3-minute rest period, the mix would be observed again to ensure the characteristics were exhibited. At this point the mix observations were used to determine whether more Type-F superplasticizer should be used and if the rest of the mixing water should be added to the mix. The addition of more superplasticizer and water are made by field observations combined with best judgement. To help ensure no major change to water cement ratio, the dosage of Type-F superplasticizer was never adjusted by more than 10 ml.

Upon completion of the final adjustments the mixer was again allowed to spin freely for 5 minutes. This last five minutes of rotating allowed for the additional components of the mix to get worked into the existing mix while also allowing the silica fume to bond with more particles and fill in more voids. During the last five minutes of the mixing the materials really began to show signs of self-compacting concrete and the final product was beginning to take form. After the 5-minute mixing period the mixer was stopped and the material was ready to be tested.

Testing

The mix was taken directly from the mixer and placed in the appropriate testing apparatus. First, the mix was tested for the appropriate spread based on the slump flow test, ASTM C1611. This was the first test to be performed based on the theory that if the mix did not spread to the appropriate distance there was no real reason to examine the mix for the other properties. Once it was determined that the mix demonstrated the proper spread the next test that was performed was the slump flow/ J-Ring test, ASTM C1621. This was done second to ensure the cementitious material and the aggregate would not segregate when flowing through the formwork and reinforcing steel. If the mix passed this test and did not show signs of segregation then the third and final test was performed. The last test that was performed on the mix was the air meter test, ASTM C231. This test was performed after the previous two since the percentage of the air entrainment may not be what the mix predicted; however, it still may be considered self-compacting concrete. The results of the three tests were combined and used to analyze the plastic properties of the mixes.

Mix 1

Table 1 SCC Mix One

Specific Gravities:												
Fly Ash	=	2.65	Unit Weight of Water	=	62.4	lbs/ft³						
Cement	=	3.15	Coarse Agg	=	2.653							
Silica Fume	=	2.20	Fine Agg	=	2.673							
Density:												
Coars Aggregate	=	2440	lbs/yd³									
Fine Aggregate	=	2373	lbs/yd³									
Design:												
% CA	=	53% (assumed)	%Sand	=	47% (assumed)							
Packing Factor	=	1.24 (Assumed)										
Wdry CA	=	desity*PF*CA%		=	1422.032	lbs/yd³	/	27	yd³/ft³	=	52.7	lbs/ft³
WdrySand	=	Bulk desity*PF*Sand%		=	1559.5356	lbs/yd³	/	27	yd³/ft³	=	57.8	lbs/ft³
Cementitious Materials	=	12000psi / 32 psi/ 2 lbs cement and fly ash		=	750	lbs/yd³	/	27	yd³/ft³	=	27.8	lbs/ft³
Silica Fume	=	0	*		27.8	lbs/yd				=	-	lbs/ft³
Fly Ash	=	27.8	*	40% Replacement	=					=	11.1	lbs/ft³
Cement	=	27.8 lbs/ft³	-		11.1	lbs/ft³				=	16.7	lbs/ft³
Water	=	(Cementitious Material +FA) * .3		=	8.88	lbs/ft³		W/C ratio		=	0.32	
HRWRA	=	135 ml/ft³ (assumed)	Air Entrainment	=	84 ml	ml (assumed)		W/C ratio (adjusted)		=	0.33	

Table 1 shows the calculations that went into the initial mix design of the first self-compacting concrete mix. The equations along with some assumptions were taken from "A Simple Mix Design for Self-Compacting Concrete." (Su, 2001, 1799-1807). The equations were designed to work for normal strength 4000 psi concrete up to 8000 psi concrete. Assumptions needed to be made since the goal was to develop a design for 6000 psi concrete. The main deviation occurred with the design of the amount of mixing water along with the superplasticizer dosage, both quantities would be varied slightly through trial and error in the various mixes. Mix 1 was the first attempt at making a self-compacting concrete mix in the lab therefore the design was heavily influenced on previous results obtained from prior research conducted by Naik et al. (2011). .

Without having any sort of general understanding how the air entrainment admixture would affect the mix the amount of admixture used was based solely on literature review and best judgement. The dosage of air entrainment used in mix one was 84ml. As the tests were conducted on mix one, the initial tests were showing that this could be a viable design and that maybe a good starting point had been established. The spread of the concrete measured out at 24 inches and 26 inches, which was right in the middle of the target area. Also, the material showed very little signs of bleeding and the material all seemed to flow with the cement. Little to no segregation was detected in the mix; however, the downfall occurred once the percentage of entrained air was determined. The mix tested out at 20% air entrainment which for expansion and contraction would be great, but for compressive strength this mix produced a very low strength of 2664 psi after 28 days.

Mix 2

Table 2 – Self-Compacting Concrete Mix Two

Makes 1 Cubic foot	Mix	% of mix based on Specific Gravity
SCC Mix Number	2	2
% Replacement of Cement with fly ash.	40.16	0.44
Cement (lb/ft^3)	16.56	0.08
Fly Ash (lb/ft^3)	11.11	0.07
Sand (lb/ft3)	56.63	0.34
Course Aggr. (lb/ft^3)	50.74	0.31
Water (lb/ft^3)	10.12	0.16
HRWRA (oz/ft^3)	4.55	No S.G. provided
Silica fume (lb/ft3)	0.00	0.00
Air Entrainment	0.00	0.00
Water Cement Ratio	0.37	
Water Cement Ratio (Including Admixtures)	0.38	

With the high percentage of air voids in the mix one the concepts for mix two was to try the mix without any air entrainment admixture. However, not placing any air entrainment into the mix would require a slightly higher amount of water to keep the water to cement ratio somewhat constant as seen in Table 2.

After the initial three minutes of mixing and three minutes of resting the mix appeared to be sticking together and not flowing in the mixer like the first mix. Since mix one produced a desirable spread and did not show signs of segregation the assumption was made that if the material in the mixer appeared similar to that of mix one, then the results would be similar. To help reach the characteristics of mix 1, the addition of 1.3 lbs of extra water was required to reach the desired characteristics of the mixing self-compacting concrete.

When the mix was ready to be tested the material was left in the mixer and taken directly from the mixer to the testing apparatuses. The first test performed was the spread test and mix two produced a spread of 21 inches and 23 inches which fits within the outline of ASTM C1621, but since the goal was to produce a spread around 24 inches this result was not great but a good point to start from. The next test that was conducted was the slump flow with the j-ring, this test did not give a great result either, the mix appeared to have some bleeding which wasn't great, also most of the aggregate sat in the middle. The last test again was for the percentage of air voids in the concrete. This gave a much more desirable result of 4.5 percent. This value is acceptable but research has shown for the maximum performance of the self-compacting concrete the percentage of entrained air should be closer to 5.5 percent. After this test was conducted it was established that the air entrainment add mixture, if used, would only be needed in very small doses, also more liquid may be needed along with Type-F superplasticizer to keep the segregation down and flowability up.

Mix 3

Given the results from mix 2, the design for mix 3 would only alter two of the previous components. The mix and the results would then be re-examined to help better understand the effects of those components on the mix. The two changes made were the Type-F superplasticizer and the addition of a small amount of silica fume as seen in Table 3. In an attempt to increase the followability of the mix, 200 ml of the Type-F superplasticizer were used compared to the 134.59 used in mix 2, along with 3 lbs of silica fume compared to no silica fume in the previous mixes.

Table 3-Self-Compacting Concrete Mix Three

Makes 1 Cubic foot	Mix	% of mix based on Specific Gravity
SCC Mix Number	3	3
% Replacement of Cement with fly ash.	40.15	0.44
Cement (lb/ft^3)	16.56	0.08
Fly Ash (lb/ft^3)	11.11	0.07
Sand (lb/ft3)	56.63	0.34
Course Aggr. (lb/ft^3)	50.74	0.31
Water (lb/ft^3)	10.12	0.16
HRWRA (oz/ft^3)	6.76	No S.G. provided
Silica fume (lb/ft3)	3.00	0.02
Air Entrainment	0.00	0.00
Water Cement Ratio	0.33	
Water Cement Ratio (Including Admixtures)	0.34	

After the eleven-minute mixing procedure was complete the mix was showing signs of a successful Self-Compacting Concrete mix. Again, the same three tests were conducted on the completed mix starting with the spread test. This produced results that were promising in the fact that the spread reached 29 inches and 30 inches. Therefore, it was established that the addition of the 65.41 ml of Type-F superplasticizer caused the spread to increase by 8 inches. However, like the previous mix the material seemed to stay piled in the middle of the J-Ring and did not flow outward with the rest of the cementitious material. The air meter test showed that the air content of the mix had dropped from 4.5 percent, in mix 2, to 3.5 percent in mix 3. The high spread may have something to do with the air content being low or the addition of the silica fume.

Mix 4

Table 4- Self-Compacting Concrete Mix Four

Makes 1 Cubic foot	Mix	% of mix based on Specific Gravity
SCC Mix Number	4	4
% Replacement of Cement with fly ash.	40.15	0.44
Cement (lb/ft^3)	16.56	0.08
Fly Ash (lb/ft^3)	11.11	0.07
Sand (lb/ft3)	56.63	0.34
Course Aggr. (lb/ft^3)	50.74	0.31
Water (lb/ft^3)	10.12	0.16
HRWRA (oz/ft^3)	5.24	No S.G. provided
Silica fume (lb/ft3)	5.00	0.04
Air Entrainment	0.00	0.00
Water Cement Ratio	0.31	
Water Cement Ratio (Including Admixtures)	0.32	

Since the air content decreased on the previous test the idea was to increase the silica fume content to 5 lbs and decrease the Type-F superplasticizer back down to 155 ml as seen in Table 4. Making these adjustments allow the mix to be closer to the composition of mix 2, this allowed for a stricter comparison between what part of the mix affected the air void ratio. So again, all the materials were mixed following the standard mixing procedure that was developed with the help of Strata and adopted for this project.

This test procedure produced results that again showed there was improvement from the previous tests while still having some room to make a couple final adjustments to help dial in the ideal design. The spread of the mix was at 22 inches and 24 inches which was right on track for the goal of the overall mix. Spread test combined with the j-ring showed that there was some slight bleeding but not an excessive amount, within the tolerances of self-compacting concrete. The air meter test produced results that were promising also, with the meter giving a result of 4.75 percent air entrainment. Again, this result is not the desired outcome, however it got the results back to what was expected from the design. This mix was promising and showed that the idea of the high range water reducer was somewhat accurate. Mix 4 allowed for the better design of mix 5.

Mix 5

This mix was by far the most successful mix of the process. That being said, the previous mixes helped understand the effects of the different aspects and how the alter the properties of the fresh concrete. For mix 5 the only property that was altered was the amount of Type-F superplasticizer. Given the data was flowing in the right direction and silica fume content was kept around 5 lbs the only change that made sense was to add 35 ml more of the Type-F superplasticizer, as seen in Table 5.

Table 5-Self-Compacting Concrete Mix Five

Makes 1 Cubic foot	Mix	% of mix based on Specific Gravity
SCC Mix Number	5	5
% Replacement of Cement with fly ash.	40.15	0.44
Cement (lb/ft^3)	16.56	0.08
Fly Ash (lb/ft^3)	11.11	0.07
Sand (lb/ft3)	56.63	0.34
Course Aggr. (lb/ft^3)	50.74	0.31
Water (lb/ft^3)	10.12	0.16
HRWRA (oz/ft^3)	6.26	No S.G. provided
Silica fume (lb/ft3)	5.00	0.04
Air Entrainment	7394.17	0.00
Water Cement Ratio	0.31	
Water Cement Ratio (Including Admixtures)	0.32	

As stated previously mix 5 was the mix that fell within all the goals of this self-compacting concrete study. For this mix a slight modification was made to original mixing procedure and that was to add all the sand right away along with the Type-F superplasticizer with the thought that if the superplasticizer was added sooner it would have more time to react with the other products in the mixer. Like the previous mixes the self-compacting concrete was left in the mixer and taken out only when needed for the tests. The slump test produced a spread of 24 inches and 26 inches respectively. This fell right within desirable range. When the material was placed in the slump test combined with the j-ring, the material flowed through the opening and there was no segregation or bleeding detected. The only test left was the air content test which had caused problems on the previous mixes. However, this time the air meter gave out a reading of 5.5 percent entrained air. This is within a half of percent of the target air content.

Control Mix

The control mix was a standard normal weight concrete that was created to compare the distribution of the aggregate throughout the cylinder, this mix was also used to set the target compressive strength. While the mix could be visually inspected to ensure the aggregate did not separate from the binder there was no solid way of proving that once the mix was cast the aggregate would stay evenly dispersed throughout the cementitious material. After curing for 3 days the distribution of the aggregate in the self-compacting concrete mixes would be compared to the distribution of the aggregate in the control mix by visual inspection.

Trial 1 Batch Volume					1,0		ft^3
Wdry CA	=	70,72	lbs				
Sand Weight	=	0,03	lbs				
Silica Fume	=	5,67	lbs				
Fly Ash	=	16,77	lbs				
Cement	=	35,38	lbs				
Water	=	11,85	lbs			Corrected 9,78	lbs
Air Entrainer	=	6	oz/cwt	=	103		ml
Type A Water Reducer	=	0	oz/cwt	=	0		ml
Type F Water Reducer	=	35	oz/cwt	=	233		ml

Figure 9 Normal Concrete Control Mix

Looking at Figure 9, it shows the materials that were used to create the control mix which produced a compressive strength of 3723 psi at 24 hrs., 7733 psi at 7 days and 9522 psi after the full 28 day curing period. These results were used to compare the overall compressive strenghts of the self-compacting concrete to ensure that the test specimens achieved a similar compressive strength.

Chapter IV

Test Results

The overall objective of this research was to develop a self-compacting concrete that would achieve an overall strength greater than 6000 psi, which would classify the mix as high strength. It was determined that for a successful high strength mix there would be certain guidelines that should be met while the mix was still plastic. The properties that would be tested and compared would be spread, pass ability, and air content. To achieve a successful self-compacting concrete the material must spread/ compact under its own weight without the help of vibratory machines. Second, the material needs to flow around the reinforcing steel without getting segregated. Finally, the last characteristic that should be met by the fresh concrete to get have approximately 6 percent entrained air. The following information explains the mix results.

Figure 10 Control mix aggregate distribution

Figure 11 Mix 5 aggregate distribution

Looking at Figures 10 and 11 it can be seen that the aggregate is evenly dispersed throughout the cylinders. Since the aggregate was evenly dispersed in both cylinders that proved that the aggregate did not sink to the bottom or separate from the binder. What that means is pressure that will be exerted on the concrete will get evenly dispersed amongst all the components of the mix ensuring that the mix is not reliant on either the cementitious material or aggregate alone.

Mix Comparison

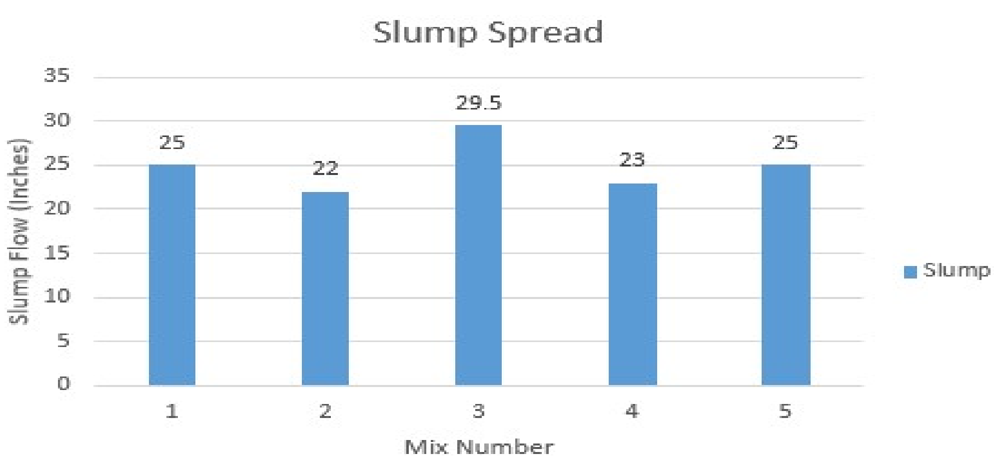


Figure 12 Slump Flow Comparison

Now that the design for all the mixes had been laid out and the test results gathered, the information was compiled and placed into charts for comparison. The first data that was examined was the spread of all the mixes which can be seen in figure 12. Looking at all the mixes, mix one and mix five both fell within the desired spread. However, all the mixes produced spreads that would classify them as a successful self-compacting concrete mixes. The strange thing about mix one and mix five being comparable is that mix one contained a low dosage of Type-F superplasticizer and mix 5 contained 50 ml more of superplasticizer. The other strange comparison was that mix 5 also contained 1.3 lbs more water than mix one. Given this data the conclusion was made that the 5 lbs of silica fume added into mix 5 helped absorb the extra 1.3lbs of water and also absorbed some of the initial water, thus requiring the additional 50 ml of Type-F superplasticizer.

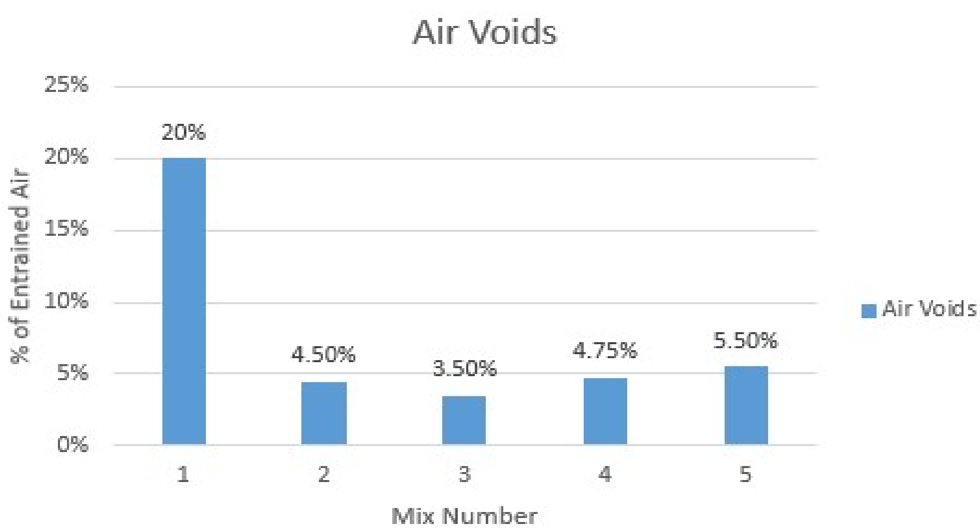


Figure 13 Entrained Air Comparison

The next information that will be examined is percentage of entrained air in each of the mixes. The comparison of entrained air in the five mixes can be seen in Figure 13. It can be seen that every mix, except for mix one, showed trends that were predicted. The data points stayed constant and that when the spread got higher, the amount of entrained air decreased. This trend was expected since larger spread means more water which equals less air voids. However, what wasn't expected was the ability to avoid using an air entrainment admixture. From all the research conducted it appeared that previous test results struggled to obtain a steady air entrainment without the use of admixtures. I believe the reason this trend was seen was due to the Type-F superplasticizer. Some data shows that using certain dosages of superplasticizer will help induce air into the mixture, but with that being said, mix 3 showed that too much superplasticizer could potentially break down the air structure and cause a low entrained air content.

Table 6 Bleeding and Segregation Comparison

	SCC Mix Number				
	1	2	3	4	5
spread	25	22	29.5	23	25
bleeding	minor	none	lots	minor	none
segregation	minor	some	some	minor	none
air voids	20%	4.50%	3.50%	4.75%	5.50%

The last plastic property comparison that was examined was the segregation and bleeding that occurred within the slump flow with j-ring. Looking at Table 6, it can be seen that as the spread got lower the amount of segregation and bleeding decrease and when the spread got large there was significant bleeding visible. Again, this is what was expected of the mix since large spreads generally mean less water was absorbed. This allows the water to flow away from the aggregate and not stick together. Therefore, the first and last mix showed promising signs with little to no segregation and little to no bleeding. That told us that no matter what mix design is used the components of that mix need to be altered slightly to adapt, that no one mix will behave exactly like the last one when you deal with a mix that has such a low water content.

Since the idea behind creating a high-performance self-compacting concrete was for the specimen to achieve a compressive strength higher than 6000 psi the specimens needed to be crushed to ensure they met the target strength. Looking at figure 14, it can be seen that all but the first mix achieved a compressive strength of at least 6000 psi after 28 days, the control mix is represented by mix 6 in the graph. To develop the graph, two cylinders of each mix design were crushed within 30 minutes of each other and the average of those two results were plotted in figure 14, the actual compressive strengths can be seen in tables 7, 8, and 9. The best performing mix was not even a mix that the plastic properties performed the best. Also, the mixes all were relatively close to each other in the early stages of the design, it was only after 28 days that the difference between the specimens started to grow. Mix three had the larger compressive strength which is largely in part to having less entrained air in the mix. While that is great for strength the low percentage of entrained air will cause the material to underperform when exposed to external elements. Therefore, mix five was considered the most successful mix since it met the desired goals of spread, entrained air, compressive strength, and showed no bleeding or segregation.

Table 7 Self-Compacting Concrete Compression tests - 24

24 HR.	SCC Mix Number				
	1	2	3	4	5
Compressive Strength (psi) average	924	3166	3510	3475	3380
Compressive Strength (psi) Spec. 1	875	2989	3752	3568	3297
Compressive Strength (psi) Spec. 2	973	3343	3268	3382	3463

Table 8 Self-Compacting Concrete Comparison tests - 7 day

7 DAY	SCC Mix Number				
	1	2	3	4	5
Compressive Strength (psi) average	1995	5211	5403	5262	5312
Compressive Strength (psi) Spec. 1	1896	5284	5568	5329	5416
Compressive Strength (psi) Spec. 2	2094	5138	5238	5195	5208

Table 9 Self-Compacting Concrete Comparison tests – 28 day

28 DAY	SCC Mix Number				
	1	2	3	4	5
Compressive Strength (psi) average	2664	8262	9793	8765	8975
Compressive Strength (psi) Spec. 1	2458	8345	9865	8676	9075
Compressive Strength (psi) Spec. 2	2870	8179	9721	8854	8875

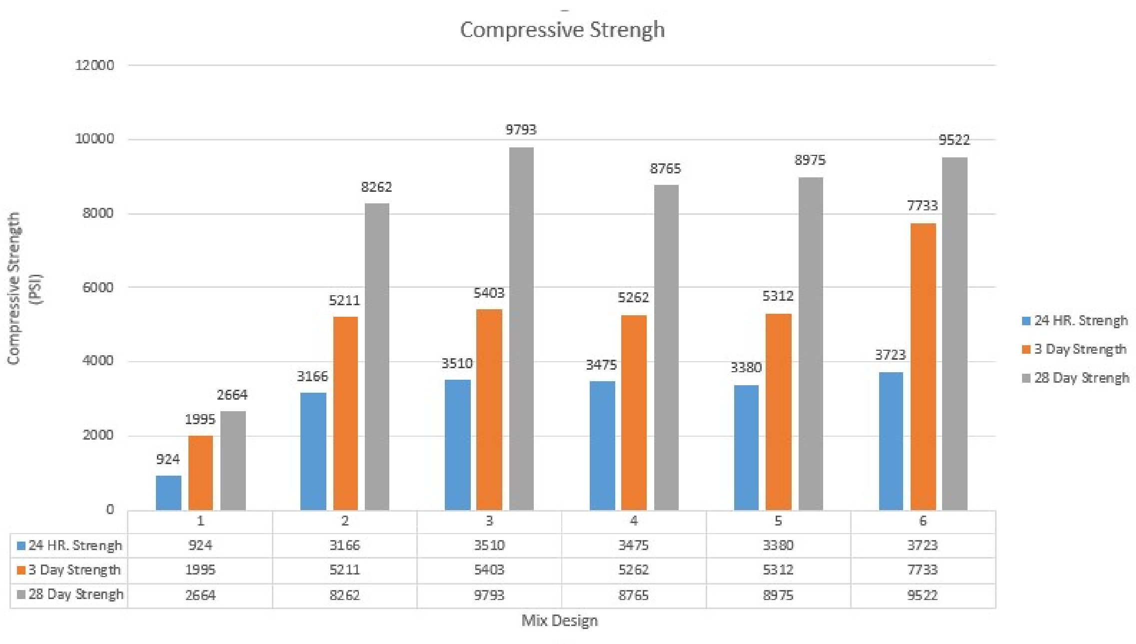


Figure 14 Compressive Strength Comparison

Chapter V

Conclusions, Limitations, and Future Works

Conclusion

By analyzing the test results and comparing the compressive strength of the control mix to the high performance self-compacting concrete it was determined that even if the plastic properties were slightly off the overall strength could still be achieved. It was also determined that with the addition of silica fume into the mix the amount of water required to keep the mix fluid was also increased. Lastly, the key figure to notice is that the self-compacting concrete was able to reach strengths similar to those achieved by normal weight high strength concrete.

However, while many theories were proved, it was also determined that no one mix would meet every need. Each mix, while different, exhibited properties that would classify them as high-performance concrete, minus mix one. Therefore, to say that a definitive mix design would be better than the others is inconclusive. It would be better to say that the design process and steps taken to develop the mix was successful and when using high-strength self-compacting concrete the admixtures will need to be altered depending on travel time and other conditions, like weather and placement style.

Limitations

While the test results begin to develop a trend, these tests were only performed in a lab environment and never in the working environment. The test conducted only gave a small look at the possible combinations that could be used to achieve the desired outcome. Also, the amount of time spent preparing the aggregate would only be feasible in a lab environment. The other downside to the lab tests was that once the mix was mixed, the material was tested right away. There was no travel time associated with the properties that were tested.

Future Studies

To expand on the research that was conducted I would recommend that more combinations of admixtures and aggregated be combined to see if other combinations produce similar or better outcomes. Also, the use of a self-compacting concrete mix in the field would give a better understanding how transport time can affect the flowability of the product. Lastly, this research was only looking at the plastic properties of the mix when the most important part of concrete is how the final product performs. The specimens should be tested for hardened properties to ensure the assumptions made during the mix design are actually correct.

Appendix

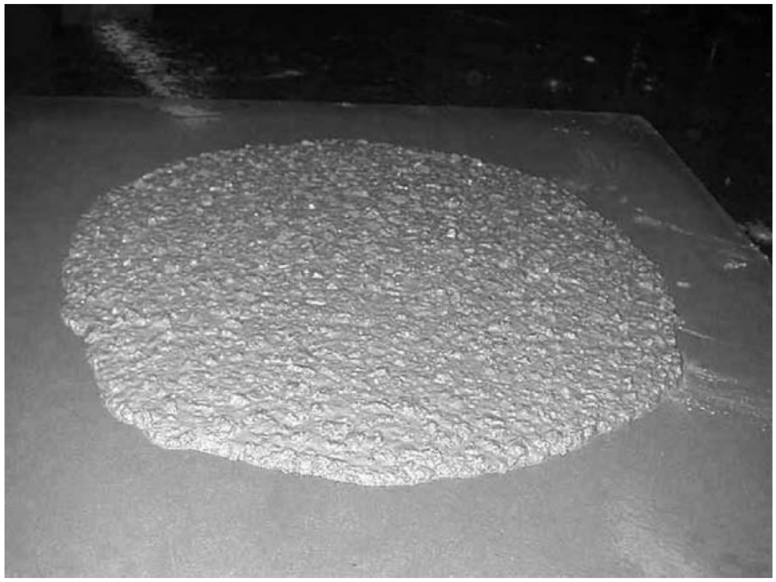
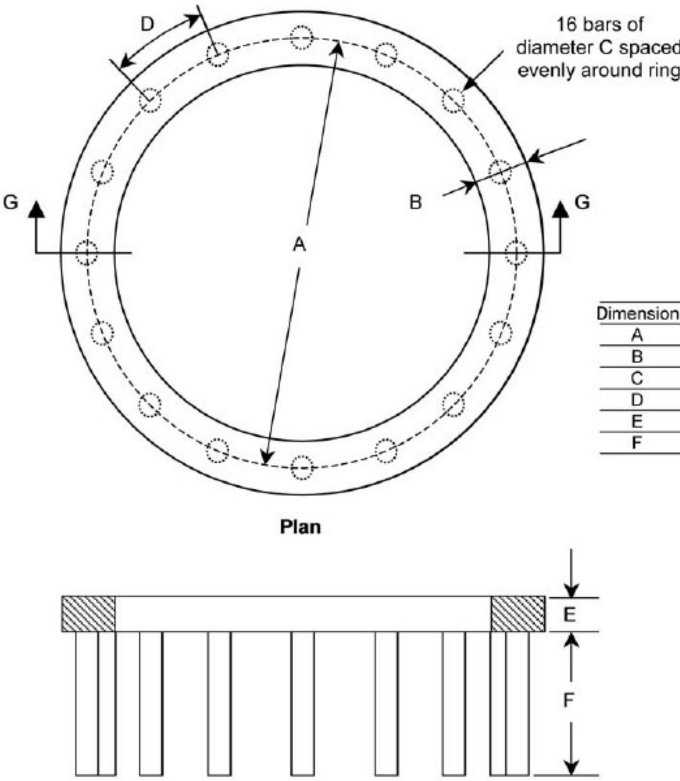


Figure 15 Correct Spread Test Result (Lu, 2014)

Figure 16 Spread Test with Bleeding (Lu,2014)

Figure 17 Spread Test with segregation (Shen, 2014)

Figure 18 Spread Test with even aggregate distribution (Shen,2014)



Dimension	in.	mm
A	12.0 +/- 0.13	300 +/- 3.3
B	1.5 +/- 0.06	38 +/- 1.5
C	0.625 +/- 0.13	16 +/- 3.3
D	2.36 +/- 0.06	58.9 +/- 1.5
E	1.0 +/- 0.06	25 +/- 1.5
F	4.0 +/- 0.06	100 +/- 1.5

Figure 19 J-Ring Layout (ASTM C1621)

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